

The $^{18}\text{O}/^{16}\text{O}$ induced proton isotope shift in water

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Measurements of proton NMR spectra at 750 MHz of dilute solutions of water in nitromethane reveals a small proton isotope shift due to $^{16}\text{O}/^{18}\text{O}$ substitution equal to about 1 ppb.

There has been much recent interest in the isotope shifts induced by the substitution of ^{18}O for ^{16}O . In the extensive review of Risley and van Etten¹ proton isotope shifts in water induced by $^{18}\text{O}/^{16}\text{O}$ substitution are reported as covering the very wide range from -70 to $+300$ ppb. In early work Pinchas and co-workers²⁻⁴ used separate samples of the pure isotopomers in order to prevent proton exchange. The strong dependence of the water shielding upon concentration, temperature and certain uncontrolled impurities makes these results questionable.

Recently, we performed measurements of the $^{18}\text{O}/^{16}\text{O}$ induced proton isotope shift using dilute solutions of an H_2^{16}O and H_2^{18}O mixture in nitromethane.⁵ At a proton NMR frequency of 300 MHz we found no splitting of the H_2O singlet. This suggested that the $\text{H}_2^{18}\text{O}/\text{H}_2^{16}\text{O}$ isotope shift is less than 0.5 Hz (about 2–3 ppb). The availability of NMR spectrometers with higher magnetic fields makes it possible to measure an isotope effect of this size. Here we describe a successful attempt to measure this isotope shift on a 750 MHz NMR spectrometer.

The crucial requirement in obtaining the NMR parameters of individual water molecules is to stop the proton (or proton-deuteron) exchange in order to prevent the collapse of spin multiplets and to exclude any effect on the NMR line shape. To obtain reliable results it is necessary to use dilute solutions of water in organic solvents.⁶ The solvent has to be carefully dried to eliminate the residual water.

We used $[\text{D}_3]\text{nitromethane}$ purchased from Merck with the deuteration levels of 99.44% ($\pm 0.01\%$) according to our estimates. The proton signal of the residual CHD_2NO_2 was used to determine the water content in the solvent. $[\text{D}_3]\text{Nitromethane}$ was dried by several freezing–thaw–pumping cycles using P_2O_5 as a drying agent *in vacuo* and passed through a series of traps to eliminate traces of the drying agent. The final water content never exceeded 0.01 mol%. We used double distilled H_2^{16}O , 99.1% H_2^{18}O and 30% H_2^{17}O enriched water purchased from Isotech and 99.96% D_2O purchased from Merck. Small amounts of D_2O were added to the solutions of water to control the rate of exchange by monitoring of the HDO lines. A small amount of dried TMS was added to control the resolution and the water line shape. We used a Young sample tube for mixing the components to control *via* ^1H NMR spectra the water content at all stages of the sample preparation. The dosages of TMS and water mixtures were done by vaporization into the precalibrated volumes. The final solution was distilled in a 5 mm sample tube and sealed under vacuum. All bulbs and sample tubes used were treated according to the procedure described earlier⁷ and kept under vacuum.

A 750 MHz Varian INOVA NMR spectrometer was used to obtain the ^1H NMR spectra. Typical proton NMR spectra of a 0.25 mol% solution of a 20 : 10 : 1 $\text{H}_2^{16}\text{O}-\text{H}_2^{18}\text{O}-\text{D}_2\text{O}$ mixture in $[\text{D}_3]\text{nitromethane}$ taken in the temperature range from 30 to 80 °C are shown in Fig. 1. Fig. 1(a) contains lines from $\text{H}_2^{16}\text{O}-$

H_2^{18}O , while Fig. 1(b) contains lines from $\text{H}^{16}\text{OD}-\text{H}^{18}\text{OD}$. Values of the $^{18}\text{O}/^{16}\text{O}$ induced proton isotope shifts were measured to be the following: 30 °C: 0.79 ± 0.05 ; 45 °C: 0.93 ± 0.05 ; 60 °C: 1.04 ± 0.05 ; 80 °C: 1.08 ± 0.05 (all values are in ppb).

It is worth noting that the water linewidth is about 0.3 Hz, revealing a decrease with temperature. In all cases the H_2^{18}O signal appears at higher field in accord with a very well known trend⁸ that heavier isotopic substitution produces high fields displacements.

In Fig. 1(b) the multiplet for HDO is shifted to high field by about 23 Hz (*ca.* 30.6 ppb), in exact agreement with the previously found H/D induced proton isotope shift for water.^{5,9} The HDO signal shows a superimposition of the triplet of HD^{16}O and that of HD^{18}O , with the two low field components of the HD^{18}O triplet almost overlapping the two high field components of the HD^{16}O signal. It is of interest that the $^{18}\text{O}/^{16}\text{O}$ induced proton isotope shift for HDO estimated from spectra at 80 °C is equal to 1.1 Hz (1.4 ± 0.1 ppb). Comparing this value with the $^{16}\text{O}/^{18}\text{O}$ induced proton isotope shift for H_2O equal to 0.86 Hz (1.08 ± 0.05 ppb at 80 °C) we can suggest an anomalously strong (0.32 ± 0.15 ppb) nonadditivity effect.¹⁰

We also performed measurements of the proton NMR of water 30% enriched by ^{17}O . According to mass spectral analysis it contains ^{16}O , ^{17}O and ^{18}O in percentages of 25.5, 30.7 and 43.7%, respectively. The ^1H NMR spectrum of a 0.5% solution of this water in $[\text{D}_3]\text{nitromethane}$ is shown in Fig. 2. Fig. 2(b)

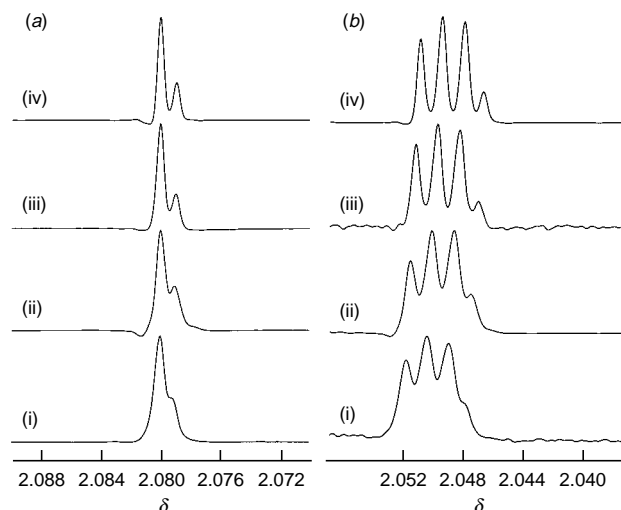


Fig. 1 Two different regions of the ^1H NMR spectrum of a 0.25 mol% solution of a $\text{H}_2^{16}\text{O}-\text{H}_2^{18}\text{O}-\text{D}_2\text{O}$ mixture in $[\text{D}_3]\text{nitromethane}$ at (i) 30, (ii) 45, (iii) 60 and (iv) 80 °C. The intensity of the signals in (b) has been multiplied by 25 compared to (a). In all four spectra the signal for H_2^{16}O is referenced to δ 1.959 to reset the temperature effect on this signal. The spectrum was recorded at 750 MHz with a sweep width of 5000 Hz, an acquisition time of 8.0 s and 1 transient. The FID was processed using slight resolution enhancement and Fourier transformed in 128 K. (a) The signal from $\text{H}_2^{16}\text{O}-\text{H}_2^{18}\text{O}$ showing the increasing values of the isotope effect. (b) The signal from $\text{HD}^{16}\text{O}-\text{HD}^{18}\text{O}$ confirming the $^{16}\text{O}/^{18}\text{O}$ isotope effect.

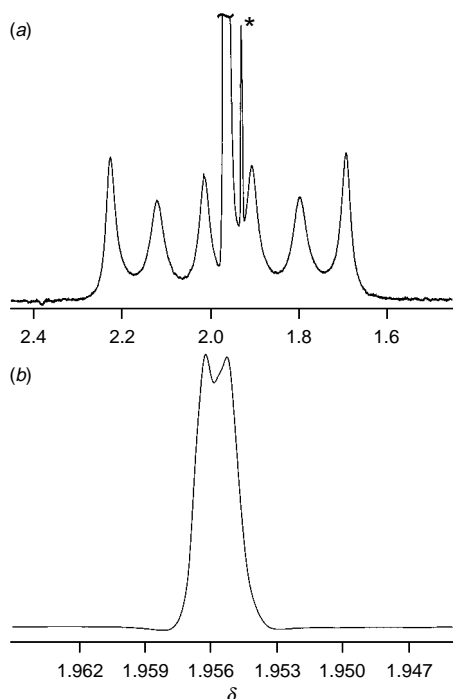


Fig. 2 The 750 MHz ^1H NMR spectrum of a 0.5 mol% solution of H_2^{16}O – H_2^{17}O – H_2^{18}O in $[\text{D}_3]\text{nitromethane}$. The spectrum was recorded at 750 MHz with a sweep width of 5000 Hz, an acquisition time of 8.0 s and 1 transient. (a) The sextet of H_2^{17}O ; the intensity of the signals has been multiplied by 100 compared to the upper trace. The signal due to HDO is marked by an asterisk (*). The FID was processed using exponential apodization and Fourier transformed in 128 K. (b) The signals corresponding to H_2^{16}O and H_2^{18}O are separated by an isotope shift equal to 1.1 ppb. The FID was processed using slight resolution enhancement and Fourier transformed in 128 K.

shows the central strong signal due to H_2^{16}O and H_2^{18}O with the $^{16}\text{O}/^{18}\text{O}$ induced proton isotope shift equal to (1.1 ± 0.1) ppb, in accord with the spectrum of pure ^{18}O water (Fig. 1).

The sextet of H_2^{17}O caused by the coupling of protons in H_2O with ^{17}O (spin 5/2) is shown in Fig. 2(a). The small signal of HDO seen to the right of the $\text{H}_2^{16}\text{O}/\text{H}_2^{18}\text{O}$ signal is due to traces of heavy water in the solvent. All components of the sextet contain additional selective broadening due to the relatively slow ^{17}O relaxation.^{11,12} The three low field components of the ^{17}O multiplet (less distorted by the central signal) have linewidths equal to ca. 20, 33 and 26 Hz, respectively, in full accord with theory.¹¹ It is interesting to note that, for a similar solution, we found in the ^{17}O NMR spectra at a similar temperature (ca. 60 °C) line widths of ca. 10 Hz.⁵ This indicates that the measurement of ^{17}O –H coupling constants is best performed using ^{17}O rather than ^1H NMR spectroscopy. We intend to obtain accurate data on ^{17}O – ^1H coupling constants and

T_1 data for ^{17}O relaxation using iterative calculations with the QUADR program.¹³ Also of interest is the possibility of checking the additivity of isotope shifts, as the $\text{H}_2^{16}\text{O}/\text{H}_2^{17}\text{O}$ isotope effect should be close to half of the $^{16}\text{O}/^{18}\text{O}$ induced proton isotope shift.

We can now state that disagreements with the old data are due to the inconsistent methods of measuring small isotope effects used in the early work.^{2–4} The data now obtained are in good agreement with other data on proton isotope shifts due to heavier isotope substitution, e.g. of $^{12}\text{C}/^{13}\text{C}$ substitution.⁸

In parallel with this experimental study, the $^{18}\text{O}/^{17}\text{O}/^{16}\text{O}$ induced proton isotope shifts were studied theoretically¹⁴ and the calculated values are in good agreement with the experimental ones.

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Notes and References

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